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MULTIPLE PILLAR COMPRESSION FAILURE IN BRITTLE ROCK

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JUNE 1985

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by

G. Swan*

ABSTRACT

Recently attempts were made at modelling multiple pillar failures which can occur in association with rockbursts. To this end the concept of spontaneous pillar collapse was evaluated using a statistical model. This model applied to the pillars at Denison Mine, Elliot Lake, gives, upon presumption of a collapse scenario, probabilities of occurrence for all possible stress levels.

An attempt was made to develop a physical model of a multiple pillar failure sequence in an 18 MN press. For the relatively small number of nine brittle pillars tested, a chain-reaction failure mode did not ensue. While this can be due to many factors, the most significant are thought to be a large coefficient of strength variation (12%) and platen tilting. The latter tends to promote segregation rather than uniform enhancement of surviving pillar stress levels.

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FRACTURES MULTIPLES DUES À LA RÉDUCTION DE LA RÉSISTANCE COMPRESSIVE DES ROCHES CASSANTES

par

G. Swan*

RÉSUMÉ

Des essais portant sur la modélisation des ruptures multiples qui peuvent se produire dans les piliers simultanément avec les coups de toit ont été effectués récemment. Par conséquent, on a fait l'évaluation du concept de l'effondrement spontané des piliers au moyen d'un modèle statistique. La modélisation de la résistance des piliers à la mine Denison à Elliot Lake donne, dans l'hypothèse d'un effondrement, les probabilités quant à la présence de toute concentration de contraintes possible.

On a essayé de mettre au point le modèle physique d'une séquence de fractures multiples dans les piliers au moyen d'une presse de 18 MN. On a utilisé un nombre relativement restreint de neuf piliers qui n'ont pas été sujet au mode de réaction en chaîne. Bien que cela puisse être fonction de plusieurs éléments, on croit que les plus significatifs sont le coefficient élevé de la variation de la résistance (12 %) et l'inclinaison du plateau. Ce dernier à tendance à favoriser la séparation plutôt que l'uniformisation de la concentration des contraintes qui subsistent dans les piliers.

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INTRODUCTION

Understanding the mechanism(s) of violent pillar failure in underground mines is as relevant and pressing today as ever. Increasingly the phenomenon of rockbursts is a routine experience for at least 16 Canadian mines currently operating. Obviously stress is a significant parameter in the context of a rockburst as with any fracture process. Exactly how stress serves to drive rock fracture to either stable or unstable failure is not, however, evident. This is particularly so in the case of mining where complex structures and geometrical configurations commonly exist. Where artificial support such as cemented backfill is placed, additional factors must be considered, Swan (1).

Various attempts at modelling certain aspects of this complex problem have been reported. Statistical models, based upon distributions of peak strengths, have been used to indicate the possibility of initiating a chain-reaction of pillar failures (2). These seem to indicate that only a small percentage of pillars need fail to precipitate a major collapse. Some amendments to this model are detailed below, irrespective of which, a priori knowledge of the pillar strength frequency distribution is vital. For the case of the room-and-pillar mines at Elliot Lake an empirical formula is available which provides expected in situ pillar strength Q_p knowing the length (L), width (w) and height (h) (3). By taking a large (>100) sample of existing pillars from this mining camp, a probability function $F(Q_p)$ that one particular pillar will sustain a stress σ_p equal to Q_p can be derived. This function, as opposed to some assumed ideal normal (Gaussian) or Weibull function, will be used below.

In recent years the numerical modelling of multi-pillar failure processes has advanced on the assumption of knowing a priori the post-failure characteristics of individual pillars. To a great extent this knowledge is

based upon data from servo-controlled testing machines loading single 'pillars' of cored rock. Qualitatively these data may be summarized as in Figure 1. By definition the curves represent various pillar sizes and a certain platen-interface condition which, given a servo-controlled press, can provide stable post-failure behaviour. The behaviour termed Class II in Figure 1 occurs when the strain energy stored in the pillar exceeds that required to fracture it. Although servo-controlled machines can accommodate this class of behaviour and maintain a state of quasi-stability, the rock mass surrounding mine pillars cannot. In any event this has led to the laboratory definition of a pillar 'brittleness' ratio (4):

$$\text{Brittleness} = E_s/E_c$$

where, E_s = Energy stored in pillar at failure load; and E_c = Energy consumed by pillar in failure process. A value greater than one (i.e., class II behaviour) serves to indicate the rock's potential to release surplus or seismic energy during failure.

Obviously, in a real multi-pillar loading environment, pillars do not act independently as though each has its own load source; complex interactions occur. Neither can the surrounding rock mass strive after stability under 'closed loop' conditions. Together these two factors limit the usefulness of conventional servo-controlled post-failure testing to suggest a lower bound, static (stable) post-failure behaviour. Unless the prototype (i.e., rock mass-pillar configuration) and model (i.e., hydraulic press-pillar configuration) are shown to be similar in respect of some as yet unkown but pertinent variable(s), nothing can be said of the actual burst potential.

A less conventional approach to post-failure testing, but one which addresses some of the above points, is to load a parallel configuration of pillars in a 'soft' machine. The platen, which is moving unidirectionally

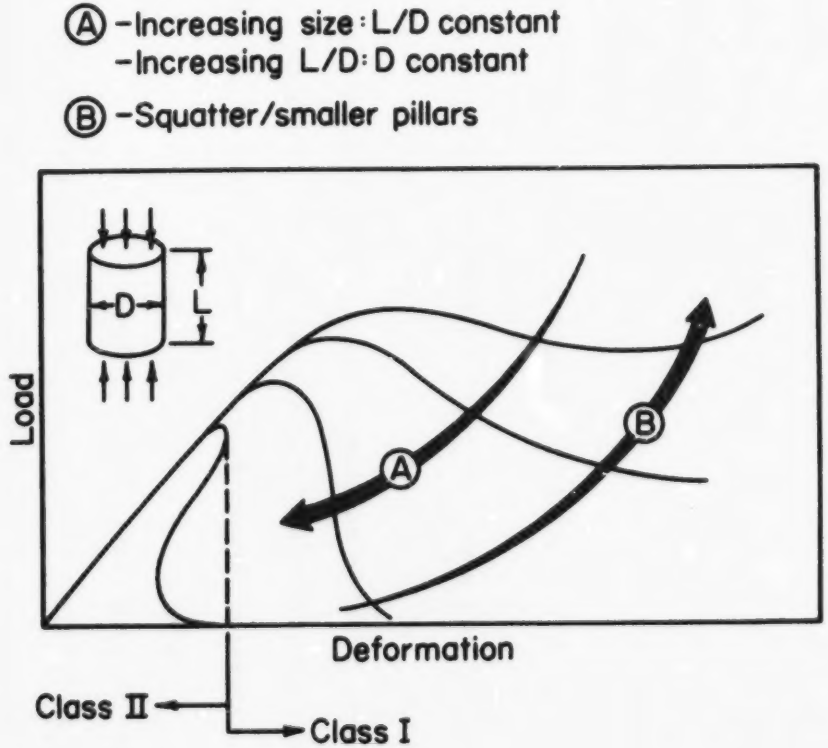

Fig. 1 - Summarized stable post-failure behaviour obtained from single pillar/servo-controlled machine configuration (5).

under load control at a slowly increasing rate, appears 'stiff' to the first pillars to fail. This is because the enhanced stress factor is still close to unity, given by:

$$\sigma_e/Q_{p,o} = n/(n - n_o) \qquad \text{Eq 1}$$

Here, n is the total number of pillars, n_o is the (small) number of initial pillars to fail at strength $Q_{p,o}$ (i.e., at stress $\sigma = \sigma_o$) and σ_e is the uniformly redistributed stress appearing on the $(n-n_o)$ remaining pillars.

While this constitutes a more correct physical modelling of the prototype room-and-pillar mine, limitations still exist. Some of these will be discussed below in reporting the results from a nine pillar test configuration carried out in a soft 18 MN press.

STATISTICAL MODELS

Statistical failure models of parallel elements have been proposed by a number of workers (2,6,7). Some are based on tensile failure. The distinction between tensile and compressive failure in such models rests purely on the possible existence of post-peak residual strength, Q_r, in the latter. This is expressed through a suitable modification of Equation 1, viz:

$$\sigma_e/Q_{p,o} = (n - tn_o)/(n - n_o) \qquad \text{Eq 2}$$

where the residual strength ratio $t = Q_{r,o}/Q_{p,o}$.

Clearly, in understanding possible mechanisms which lead to chain-reaction type pillar failures, the probability of a simultaneous occurrence of a number of pillar failures must be examined. In (2) it was assumed (though not explicitly stated) that the failure of any one pillar was an exclusive event: the probability of the simultaneous survival of all remaining pillars was taken as 1. Upon the further assumption of normally distributed strength with standard deviation 0.1 Q_p, Q_p the mean, this model obtains the

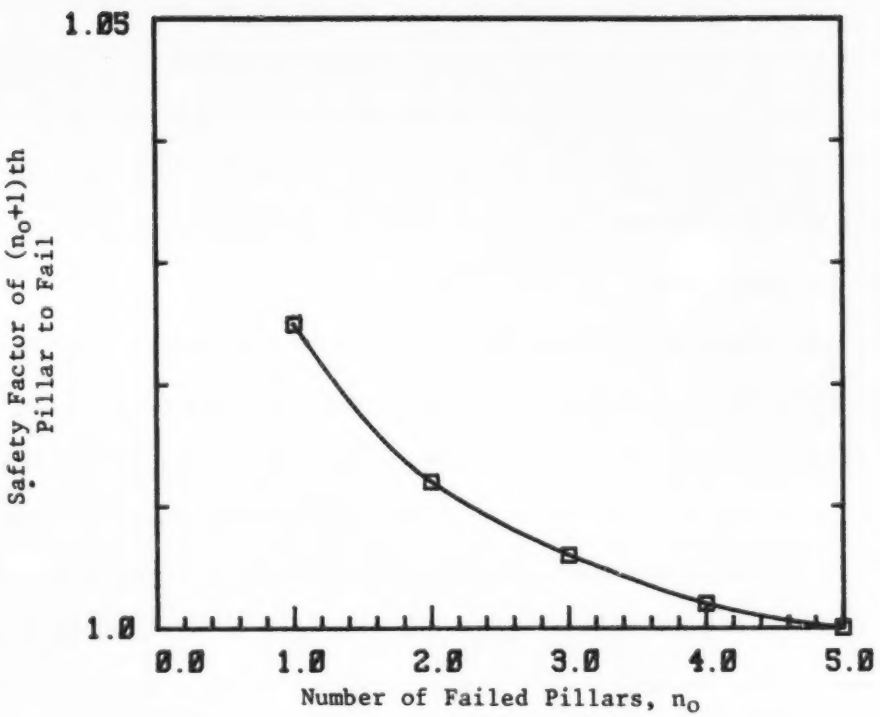

Fig. 2 - Safety factor of the (n_o+1)th pillar to fail in a sequence of 1,2,3...n_o failures, n = 100. After (2).

relationship shown in Figure 2 for 100 pillars.

A more correct approach to the problem was detailed in (7), and this forms the basis of what follows. Essentially, the probability of a total simultaneous collapse of n pillars can be calculated by considering the individual probabilities of all possible combinations of failure and survival. This becomes quite complex so details will be omitted here. Some results for 100 pillars are plotted in Figure 3 showing the probabilities of spontaneous collapse for a range of standard deviations. It can be seen that the larger the strength dispersion the lower the stress that can be sustained before a spontaneous collapse is likely.

This same model can, of course, be applied to an actual distribution of mine pillar strengths. At the Elliot Lake room-and-pillar mines an impressive quantity of data relates pillar dimensions to in situ strength (3). Accordingly, a survey of existing pillars in Denison Mine was made from stopes 11000 through to 41000 which all lie at an approximate depth of 600 m below surface. A frequency polygon of expected strength is plotted in Figure 4. This provides a mean strength of 95.90 MPa and a standard deviation of 16.36 MPa. The statistical model used to produce Figure 3 for a normal distribution can now be applied to a discrete probability function $F(Q_p)$ derived from Figure 4. The results for n=20 and 100 are plotted in Figure 5. Residual strength effects are included, as is the result of assuming a normal strength distribution with a coefficient of variation D=0.171.

For pillar design purposes a 50% probability of spontaneous collapse can now be used to suggest an upper limit for the extraction ratio R. Tributary area theory provides the relevant relationship (3):

$$\sigma_p/S_o = 1/(1 - R) \qquad \text{Eq 3}$$

where, σ_p, the average pillar stress, will equal initiation stress σ_o in the

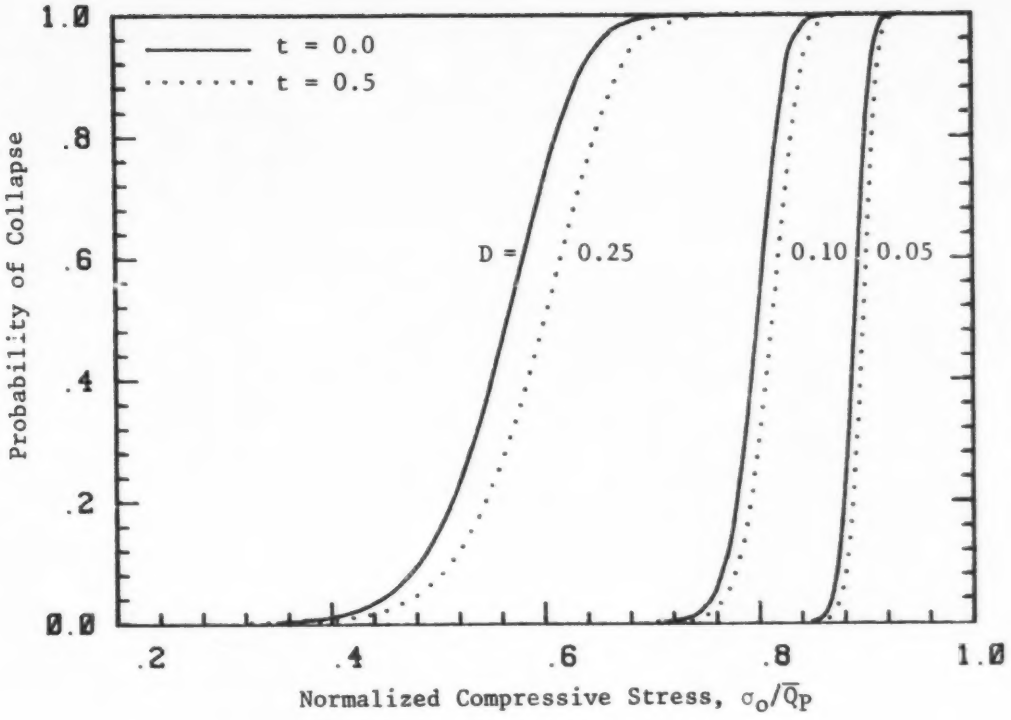

Fig. 3 - Probability of a spontaneous collapse of 100 pillars. A normal distribution of pillar strengths is assumed with coefficients of variation, D = 0.25, 0.10 and 0.05. Parameter t is the residual strength ratio Q_r/Q_p.

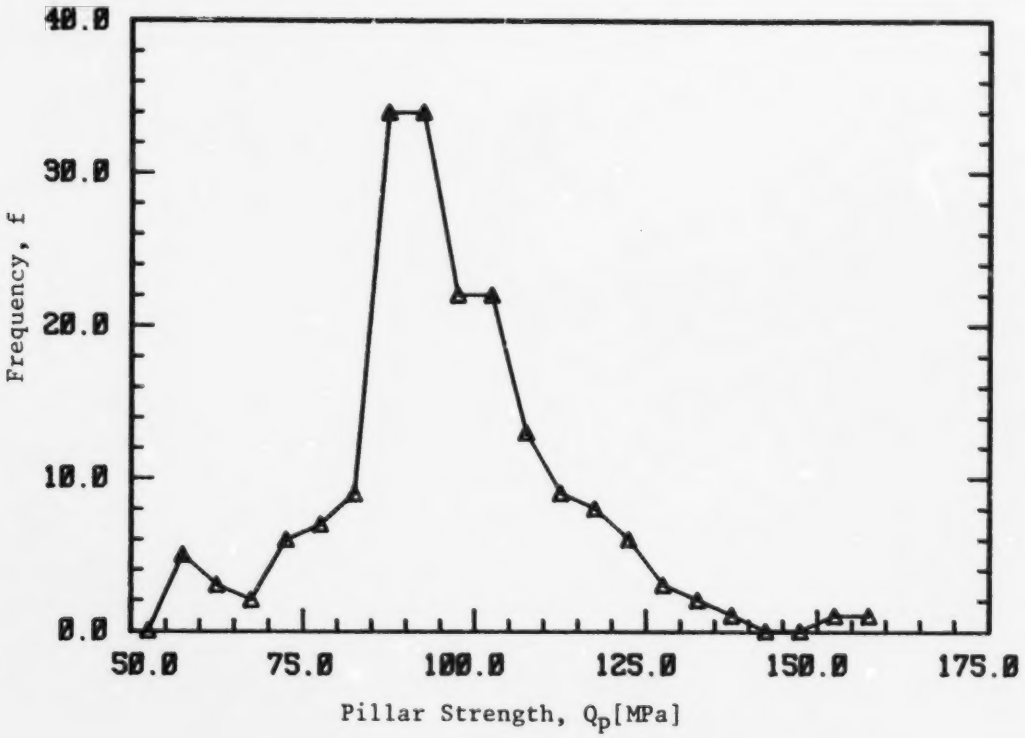

Fig. 4 - Frequency polygon of Denison Mine pillars, stopes 11000-41000, based upon 188 observations

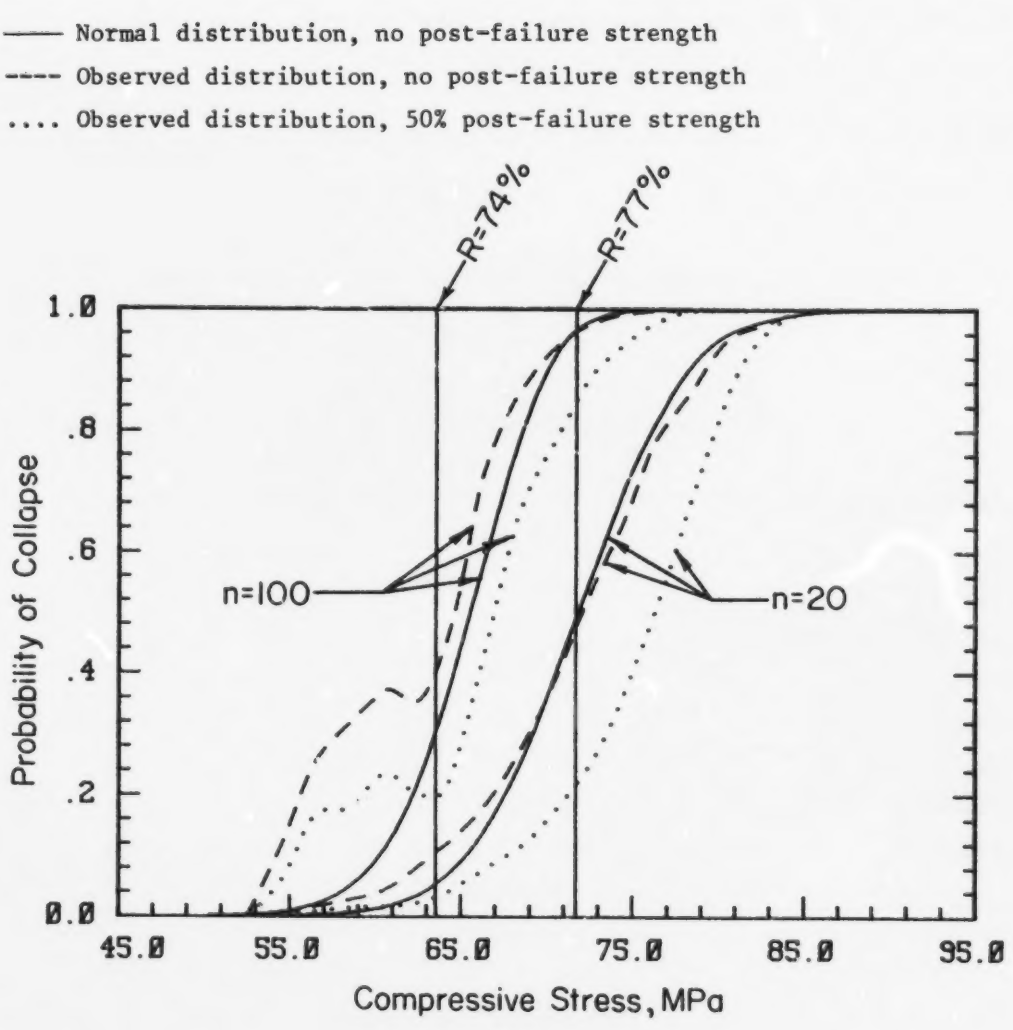

Fig. 5 - Probability of pillar collapse at 600 m depth, Denison Mine. The two vertical lines are the stress levels calculated from tributary area theory, R=74 and 77%.

limit. Here S_o is the assumed perpendicular field stress, magnitude 16.5 MPa at the appropriate depth of 600 m. For the various conditions, Figure 5, limiting extraction ratios are provided in Table 1. The results show that the chances are even for the least severe case of 20 pillars collapsing spontaneously to a residual strength of 50% of their peak strength when the extraction ratio equals 78%.

Table 1 - Extraction ratios which provide an even chance of spontaneous pillar collapse

Distribution $F(Q_p)$	Residual Strength Ratio, t	No. of Pillars n	Extraction Ratio, R
Normal, D=0.17	0.0	100	0.75
Normal, "	0.0	50	0.76
Normal, "	0.0	20	0.77
Discrete, Fig. 4	0.0	100	0.74
Discrete, "	0.0	50	0.75
Discrete, "	0.0	20	0.77
Discrete "	0.5	100	0.75
Discrete "	0.5	50	0.77
Discrete "	0.5	20	0.78

DISCUSSION

The result of applying this model to Denison Mine pillars and using approximate stress levels thought to exist at a depth of 600 m (i.e., 31-33 panel pillars) suggests the following:

a) a normally distributed strength function is adequate in such model work (see Figure 5);

b) assuming backfill will provide a residual strength given by t=0.5 (1), for

and no backfill wins approximately only 1% in additional reserves;

c) for currently applicable extraction levels (generally 74% according to (11)) the probability of a spontaneous collapse of 20 pillars is less than 10%. While this represents the least severe case considered, it is thought to be the most likely. This can be stated on the basis of applying the same model to Quirke Mine (12) where stress levels in excess of Denison Mine have occurred without promoting a severe (i.e., 100 pillar) multi-pillar collapse situation.

d) further to the statements in c) the model cannot of itself predict the actual severity of collapse that any given mine will experience. Rather, on the presumption of an expected scenario, it provides the probabilities of that occurrence for all possible stress levels. It remains unanswered what is the expected scenario leading to a group (or groups) of pillars collapsing and will remain so until a clear understanding of failure mechanisms and energy requirements is established.

EXPERIMENTAL MODEL

The statistical models described above are based upon assumptions which can ostensibly be met in a hydraulic press loading a large number of pillar specimens. In this case the total load will, in principle, be equally distributed over all intact pillars since the platen is essentially rigid and not deformable. To the author's knowledge no experimental work has been reported for such a configuration. Even post-failure behaviour, which is likely very dependent upon adjacent roof-pillar interaction effects, has, surprisingly, been investigated in single specimen testing only. Post-failure control giving stable fracture is a pre-condition of such work. Obviously, no such pre-condition applies in mines or rockbursts would never (or rarely) be observed.

Previous work with a soft 18 MN press (8) has suggested the possibility of obtaining post-failure load-deformation behaviour of extremely brittle rock by parallel stiffening elements (5). In a parallel arrangement of n rock pillars the steel element used in (8) is emulated initially by surviving pillars. An experiment of this type is now described.

TEST SET-UP

From a number of possible configurations for parallel pillar compressive loading the one finally chosen is shown schematically in Figure 6. In this design the load on each pillar is monitored independently and deformation can be calculated at any point in the plane of the platen. The scheme includes an unfailing centre pillar of aluminum (diameter 200 mm) which serves two purposes. First, it represents mine abutments or barrier pillars since it will not fail, yet possesses a deformation modulus of the order of rock (i.e., 70 GPa). Second, since it does not fail, it provides a reliable strain signal for triggering a computer-based data acquisition system. The rational sampling of pillar loads then proceeds by monitoring the centre pillar only; complete data is acquired at pre-set signal levels (see Appendix A). Several other features of the overall configuration are worth commenting upon:

1. Removal of the spherical platen head ensures that when any particular pillar fails the imbalance of forces will have no drastic effect upon the parallelism of platen contacts. A measurable amount of tilting still occurs, however, since the press hydraulic ram cannot be perfectly rigid in response to a couple acting in its axial plane. The clumping of pillars will reduce this effect, particularly when a large number of pillars comprise each clump. Without knowing the desirability (or possibility) of eliminating this effect, its magnitude was observed for

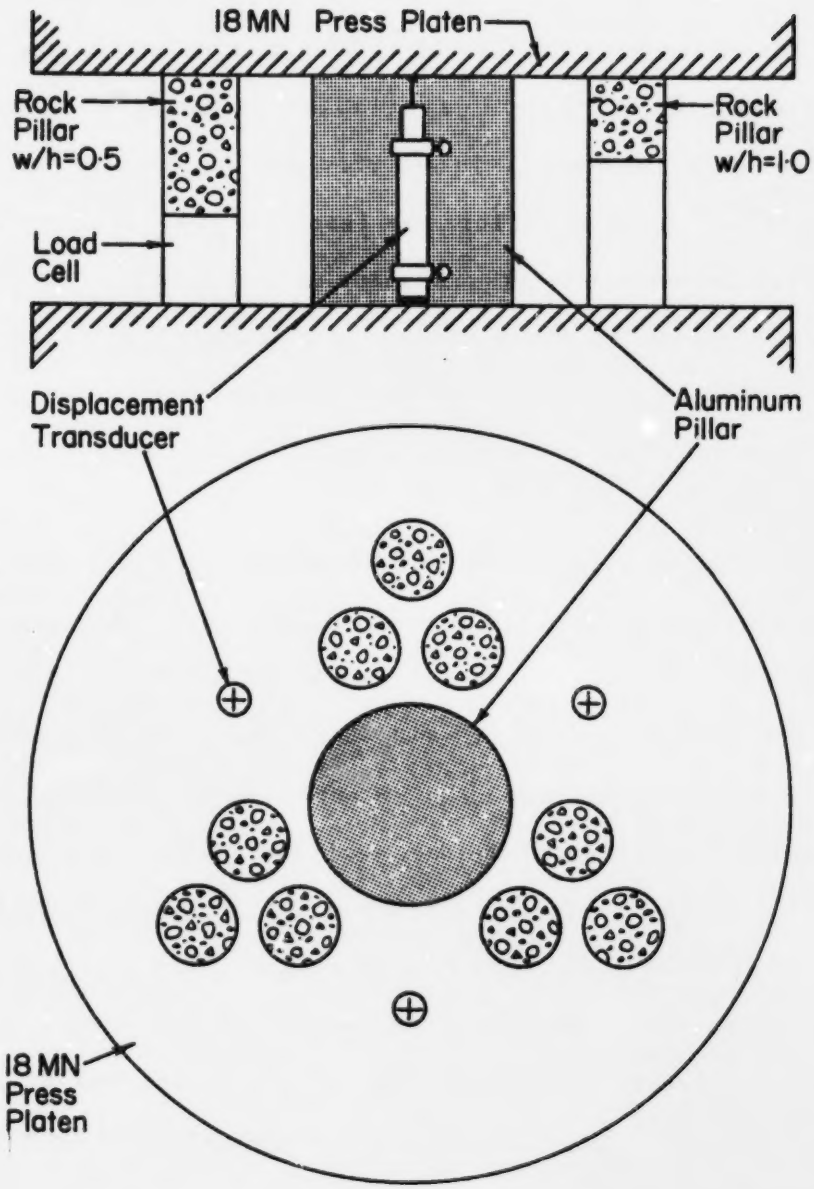

Fig. 6 - Schematic showing experimental arrangement of parallel pillars and monitoring devices.

the 3 clumps of 3 pillars, Figure 6.

2. In order to establish a uniform load on all pillars, extremely precise preparation of the overall load cell/pillar length is necessary. This can become a time-consuming process of trial-and-error unless sophisticated grinding/polishing equipment is available. It was finally decided to accept a variation in overall length provided the standard deviation of the mean pillar stress at failure was less than 10%. Since no two rock pillars have the same strength distribution (see above), the experiment represents a system in which stress and strength exhibit a defined variation. This is a situation probably quite representative of reality (see (2)), though one no longer analogous to the statistical model developed above.

3. Rock core for the experiments was 76.2 mm diameter Creighton Mine Quartz-Biotite-Gabbro whose detailed properties are reported elsewhere (9). Suffice to note that it has a deformation modulus of 65.3 $\pm$ 5.5 GPa and a uniaxial compressive strength of 199.1 $\pm$ 12.4 MPa for this specimen size. The latter figure means that up to 18 parallel cores can be loaded to failure without, and 10 with, the centre pillar. Preferably, a compromise should be attempted by arranging sufficient initial gap between platen and centre pillar so that as many as 14-15 rock pillars can be used. The entire shedding of failure load from this many pillars would yield the aluminum in the present experiment, however. Thus, nine rock pillars were chosen and an initial gap of 0.4 mm insured against yielding should all nine fail simultaneously.

4. The possibility of mixing the pillar width (w), to height (h) ratio is worth considering. Field observations in the Elliot Lake mines have suggested a differentiation in the violence of sill and rib pillar failures (10). The sills with w/h $\simeq$ 1.25 fail violently compared to the

ribs, with w/h ≃ 0.71. This surprisingly contradicts the findings of single specimen post-failure experiments that increasing w/h tends to promote stable failure, Figure 1. In the experiment reported below, a mixture of 3 pillars, w/h = 1.0 and 6 pillars, w/h = 0.5 was used.

INSTRUMENTATION

The pillars were loaded in an 18 MN Gilmore 302D closed-loop electro-hydraulic testing machine. Stiffness characteristics for this machine have been measured and are detailed in (8). Pillar load cells were custom-built mild steel cylinders with a simple strain-gauge configuration (2 axial gauges, diametrically opposite). The three displacement transducers were of type SE371/DCDC with range ±5 mm (manufactured by SE Labs). All analog signals were converted for digital acquisition by a 16 channel A/D converter with a 30 kHz conversion rate and 12 bit accuracy (manufactured by Tecmar Inc.). A Heath Zenith Z100 micro-computer was used to control and store data from the fourteen transducers active during the experiment (9 load cells, 3 displacement transducers, the press load cell and the centre pillar load cell).

RESULTS

Complete load, deformation data were recovered up to a point in the experiment when a maximum of three pillars remained intact. Corrections for tilting of the ram platen were necessary as can be seen, for example, from the pillar 2 data plot, Figure 7. These were duly implemented so that true pillar load-displacement could be observed. An example plot for pillar 2 is shown in Figure 8. Unfortunately there is no realization in any of these data of real time so that only failure sequence can be determined. This is depicted in Figure 9, which also includes the extent of post-failure behaviour for each pillar as reflected in apparent axial deformation. The term 'apparent' is

necessary since during periods of unstable pillar collapse significant deformations occur at a rate in excess of the A/D conversion. This can be observed in Appendix B, Figures B-1, B-3, B-6, B-8, where apparently large deformations accompany unstable failure. Avoiding any interpretation of these data here, stress-strain plots were prepared for pillars 2 and 4 which exhibited stable failure only. These are shown in Figure 10.

DISCUSSION

Clearly, multiple pillar tests demand a high degree of experimental sophistication in order to achieve satisfying results. While the present set-up has good capability, the following improvements should be considered:

a) load cells to be fully strain-gauged to account for tilting effects. There is good reason to believe the steepening load-deformation behaviour shown by certain pillars prior to failure (e.g., pillar 06) is erroneous;

b) width-to-height effects investigated by varying diameter, keeping pillar length constant. This will model more closely the typical room-and-pillar mine prototype;

c) the effect of platen tilting upon dynamics of failure within the pillar system is to segregate rather than distribute the shedding load(s). This can be seen in Figure 9 where, in spite of the stable failure of pillar 4, pillars 8 and 6 became unstable due to a preferred redistribution of load. Surprisingly, the next group to fail (comprising pillars 1, 2 and 3) did so with much less violence (see Figure 9, Figures B-2, B-3 and B-1). It is considered that an experimental design which has the aluminum pillar in the form of an enclosing ring would alleviate these effects. Rock pillars could then be assembled close to the ram axis. Furthermore, various types of backfill material could be placed between the pillars and enclosing ring. In the absence of field evidence for a plane, rigid type of

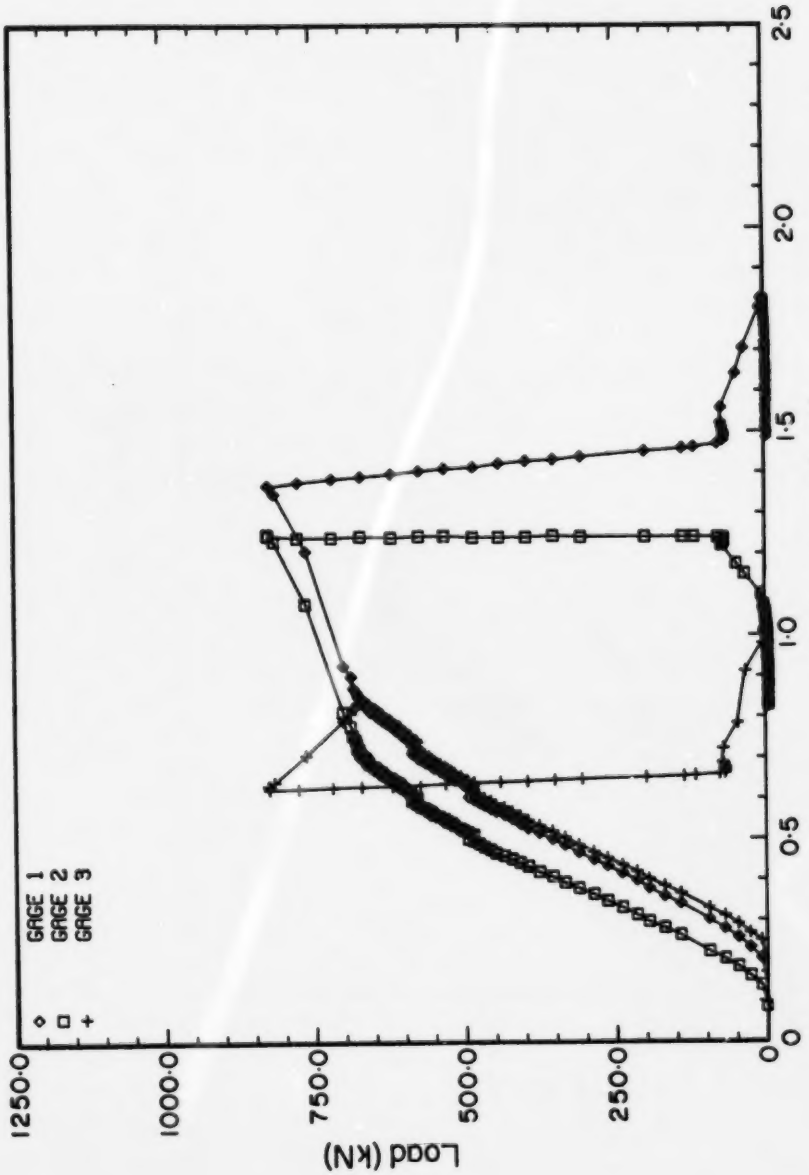

Fig. 7 - Load-deformation data recovered after test for pillar 2.

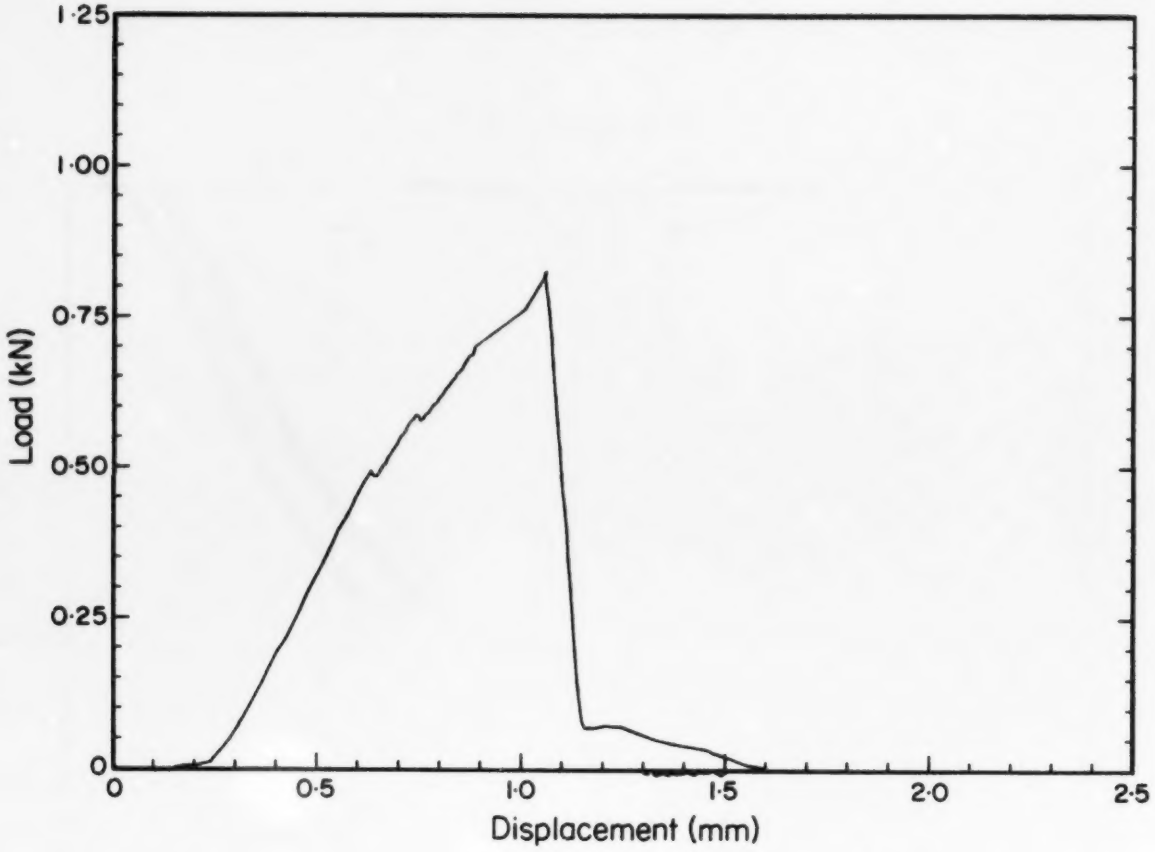

Fig. 8 - Load-deformation behaviour of pillar 2 based on Figure 7. Data corrected for platen tilting.

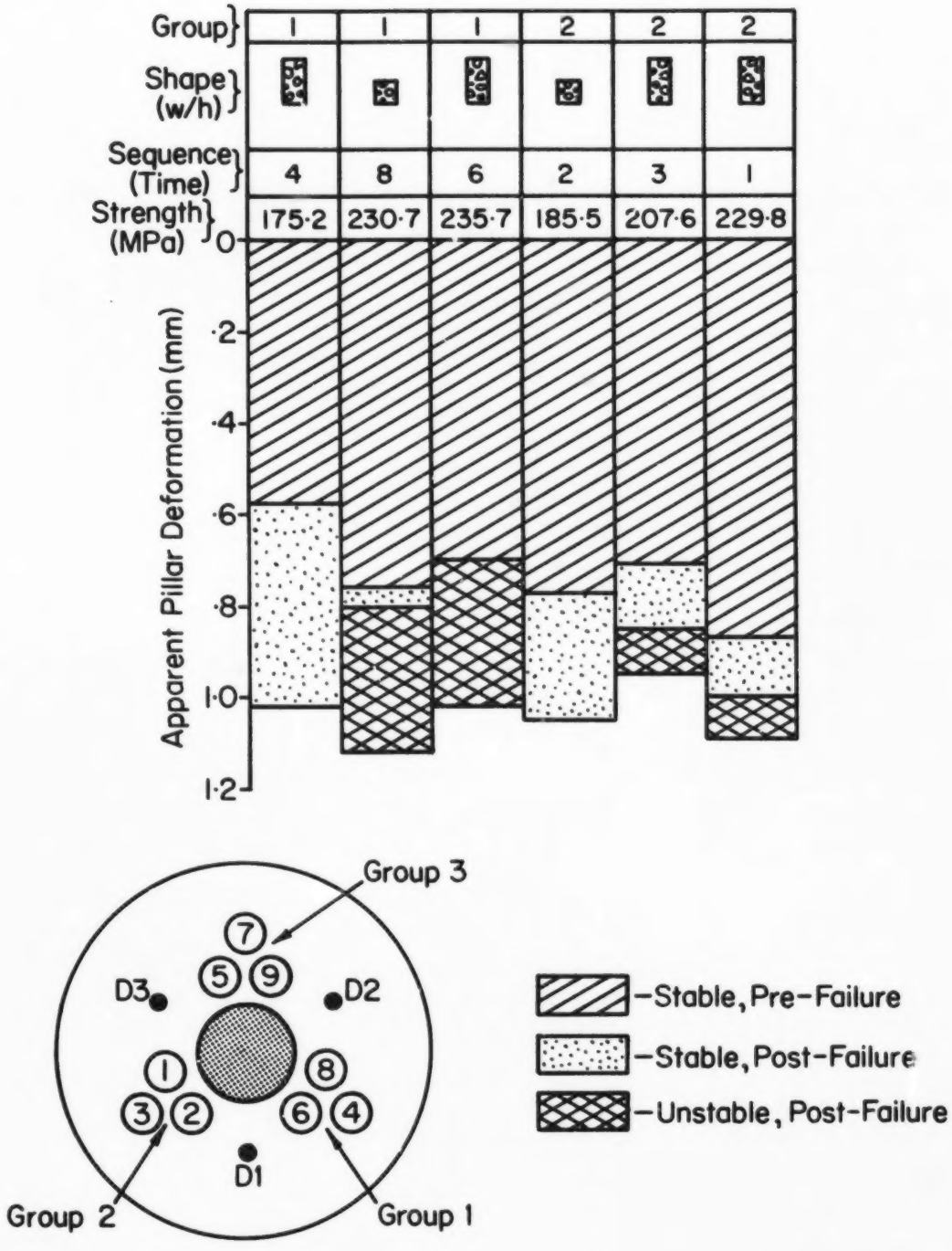

Fig. 9 - Summary of pillar failure behaviour and sequencing.
See Appendix C for appearance of specimens.

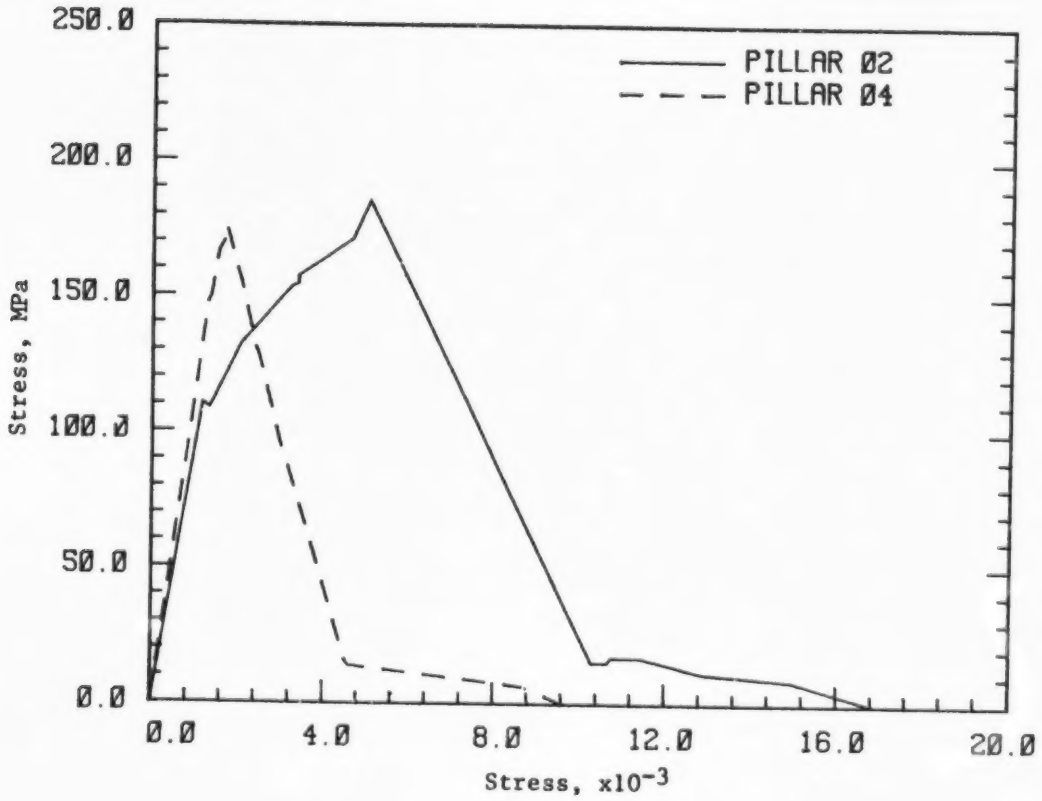

Fig. 10 - Stress-strain behaviour of pillars 02 and 04, both of which failed under stable conditions. Note: w/h=1.0 for pillar 02; w/h=0.5 for pillar 04.

ring. In the absence of field evidence for a plane, rigid type of roof/floor movement, the desirability of eliminating tilting effects altogether is dubious;

d) the validity of the statistical model applied to this experimental configuration is doubtful because of the non-uniform stress distribution prior to failure and the tilting effects which immediately accompany failure. Assuming these are eliminated and taking the aluminum pillar integral with the press (since it does not fail) an even chance of spontaneous collapse is calculated to occur at 181.2 MPa.

ACKNOWLEDGEMENT

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APPENDIX A

COMPUTER LISTING OF FORTRAN IV PROGRAM

FOR CONTROLLING AND SAMPLING TEST DATA

```
      PROGRAM MULTPIL
C***PROGRAM FOR CONTROLLING AND SAMPLING MULTI-PILLAR TEST
      DIMENSION INAME(6),ZPIL(9),ZDIS(3),CC(9),DC(3)
      DIMENSION STDATA(14,700)
      DATA SD,ED,AD/1HS,1HE,1HA/
C***CALIBRATION DATA FOR NINE LOAD CELLS,[MN/Volt]
      DATA CC(1),CC(2),CC(3),CC(4)/0.7590,0.6988,0.6863,0.7580/
      DATA CC(5),CC(6),CC(7),CC(8)/0.7677,0.7677,0.7645,0.7873/
      DATA CC(9)/0.7708/
C***CALIBRATION CONSTANTS;CP=CENTER PILLAR,PC=PRESS,DC=DISPLACEMENT
C***CP [MN/Volt];PC [MN/Volt];DC [mm/Volt]
      CP=5.066
      PC=24.575
      DC(1)=1.6408
      DC(2)=1.6494
      DC(3)=1.6844
      SFOR=0.
      VNCP=0.
C***SAMPLE LEVEL INCREMENT [Volt]
      S=0.004
C***DATA FILE ACCESS
      WRITE(1,340)
340   FORMAT(1X,'GIVE OUTPUT FILE:XXXXXXXXDAT:')
      READ(1,341)INAME
341   FORMAT(6A2)
      WRITE(1,342)INAME
342   FORMAT(1X,6A2,/,1X,/)
      DO 67 I=1,3
      ZDIS(I)=0.
67    CONTINUE
      ZPRE=0.
      ZALP=0.
C***  INPUT RANGE,A/D: +-2.5V
      IS=1
      DO 66 I=1,9
      ZPIL(I)=0.
66    CONTINUE
      WRITE(1,53)
53    FORMAT(1X,'**PROGRAM SAMPLES 14 ANALOGUE SIGNALS:**',
     1  /1X,'CHANNEL       0=CENTER PILLAR LOAD',/1X,
     2      'CHANNELS    1-9=LOAD CELLS (8)',/1X,
     2      'CHANNEL      10=PRESS LOAD',/1X,
     3      'CHANNELS 11-13=PILLAR DISPLACEMENT '//)
      WRITE(1,60)
60    FORMAT(1X/1X,'PROGRAM IN TWO PARTS;SLOW MANUAL A/D SAMPLING',
     1  /1X,          'RATE,FINAL STAGE AUTOMATIC  USING CENTER PILLAR',
     2  /1X,          'LOAD LEVEL. ZERO READINGS ARE TAKEN ON 1st SCAN.')
      ISCAN=0
51    FORMAT(A1)
55    WRITE(1,52)
52    FORMAT(1X,'**END        BY HITTING ERETURN**',/1X,
     1            '**AUTOMATIC BY HITTING ARETURN**',/1X,
     2            '**SLOW      BY HITTING SRETURN** :')
      READ(1,51)AS
C***CLEAR DONE BIT
```

```
        ICLEAR=INP(Z'14')
        IF(AS.EQ.ED)GOTO555
        IF(AS.EQ.SD)GOTO679
C***AUTOMATIC SAMPLING ON CENTER PILLAR LOAD LEVEL
200     CALL AINC
        CALL OUT(Z'14',Z'00')
        CALL SAMP(FNC)
        DIF=ABS(VNCP-FNC)
        IF(DIF.LT.S)GOTO200
        VNCP=FNC
        STDATA(1,IS)=FNC
        DO 688 I=2,14
        CALL OUT(Z'14',Z'00')
        CALL SAMP(FNC)
        STDATA(I,IS)=FNC
688     CONTINUE
        ASTOP=INP(Z'0F4').AND.Z'7F'
        IF(ASTOP.EQ.Z'45')GOTO555
        IS=IS+1
        GOTO200
C*** MANUAL SAMPLING WITH PRINT OUT
679     CALL AINC
        DO 690 I=1,14
        CALL OUT(Z'14',Z'00')
        CALL SAMP(FNC)
        STDATA(I,IS)=FNC
690     CONTINUE
        WRITE(1,325)
        SFOR=0.
        DO 610 I=1,9
        I1=I+1
        FNCL=STDATA(I1,IS)*CC(I)-ZPIL(I)
        IF(ISCAN.EQ.0)ZPIL(I)=FNCL
        STRESS=FNCL/4.5149E-3
        FORCE=FNCL*1.E3
        SFOR=SFOR+FORCE
        WRITE(1,323)I,FORCE,STRESS
323     FORMAT(1X,2X,I2,2X,F7.1,3X,F7.1)
610     CONTINUE
C***PRESS LOAD READING
        FNPC=STDATA(11,IS)*PC-ZPRE
        IF(ISCAN.EQ.0)ZPRE=FNPC
        WRITE(1,320)FNPC
320     FORMAT(1X,'PRESS LOAD READING          ='F8.3' MN')
C***DISPLACEMENT READING
        DO 563 I=1,3
        I1=11+I
        FNCD=STDATA(I1,IS)*DC(I)-ZDIS(I)
        IF(ISCAN.EQ.0)ZDIS(I)=FNCD
        WRITE(1,321)I,FNCD
321     FORMAT(1X,'PILLAR DISPLACEMENT GAGE'I3'='F8.3' mm')
70      FORMAT(1X,E12.4)
563     CONTINUE
C***CENTRE PILLAR READING
        VNCP=STDATA(1,IS)
        FNCP=STDATA(1,IS)*CP-ZALP
        IF(ISCAN.EQ.0)ZALP=FNCP
```

```
      WRITE(1,399)FNCP
399   FORMAT(1X,'CENTRE PILLAR LOAD READING ='F8.3' MN')
325   FORMAT(1X,/,1X,/,1X,'PILLAR      LOAD     STRESS'/,
     1        1X,'  NO.         kN         MPa')
      ISCAN=1
      SFOR=(SFOR/1000.)+FNCP
      WRITE(1,330)IS,SFOR
      WRITE(1,333)
333   FORMAT(1X)
      IS=IS+1
      GOTO55
555   CALL OPEN(9,INAME,2)
C***OPEN DISC FILE,WRITE DATA
C***FNPC=PRESS LOAD
C***FNDC=DISPLACEMENT GAUGE
C***FNCL=PILLAR LOAD CELLS
C***FNCP=CENTRE PILLAR LOAD
71    FORMAT(1X,13F6.3)
330   FORMAT(1X,'SAMPLE'I4',PILLAR LOAD SUM ='F8.3' MN')
      WRITE(9,74,ERR=999,END=999)IS
      DO 457 IK=1,IS
      WRITE(9,71,ERR=999,END=999)(STDATA(IJ,IK),IJ=2,14)
457   CONTINUE
74    FORMAT(1X,I4)
999   STOP
      END

      SUBROUTINE SAMP(FNC)
C*** WAITS FOR DONE BIT,SAMPLES HIGH AND LOW BITS
      ADC=0.0012266425
300   IEOC=INP(Z'10')
      IZERO=IEOC.AND.Z'80'
      IF(IZERO.EQ.0)GOTO300
      CALL INPUT(IHBIT,LBIT)
      FNC=FLOAT(IHBIT*256+LBIT)*ADC
      RETURN
      END

      SUBROUTINE INPUT(IHBIT,LBIT)
C*** SAMPLES HIGH AND LOW BITS
      LBIT=INP(Z'12')
      IHBIT=INP(Z'14')
      IF(LBIT.LT.0)LBIT=LBIT+256
      RETURN
      END

      SUBROUTINE AINC
C***TECMAR A/D AUTOMATIC INCREMENTING
      CALL OUT(Z'10',Z'04')
      CALL OUT(Z'12',Z'FF')
      CALL OUT(Z'14',Z'00')
      CALL OUT(Z'12',Z'00')
      CALL OUT(Z'10',Z'00')
      RETURN
      END
```

APPENDIX B

PILLAR LOAD-DISPLACEMENT PLOTS FOR PILLARS 01-09

Note: Displacement has been corrected for platen tilting only. Each figure is accompanied with a variety of arrowed codes. These codes indicate the commencement (1) and conclusion [1] of post-failure in the adjacent pillar 1.

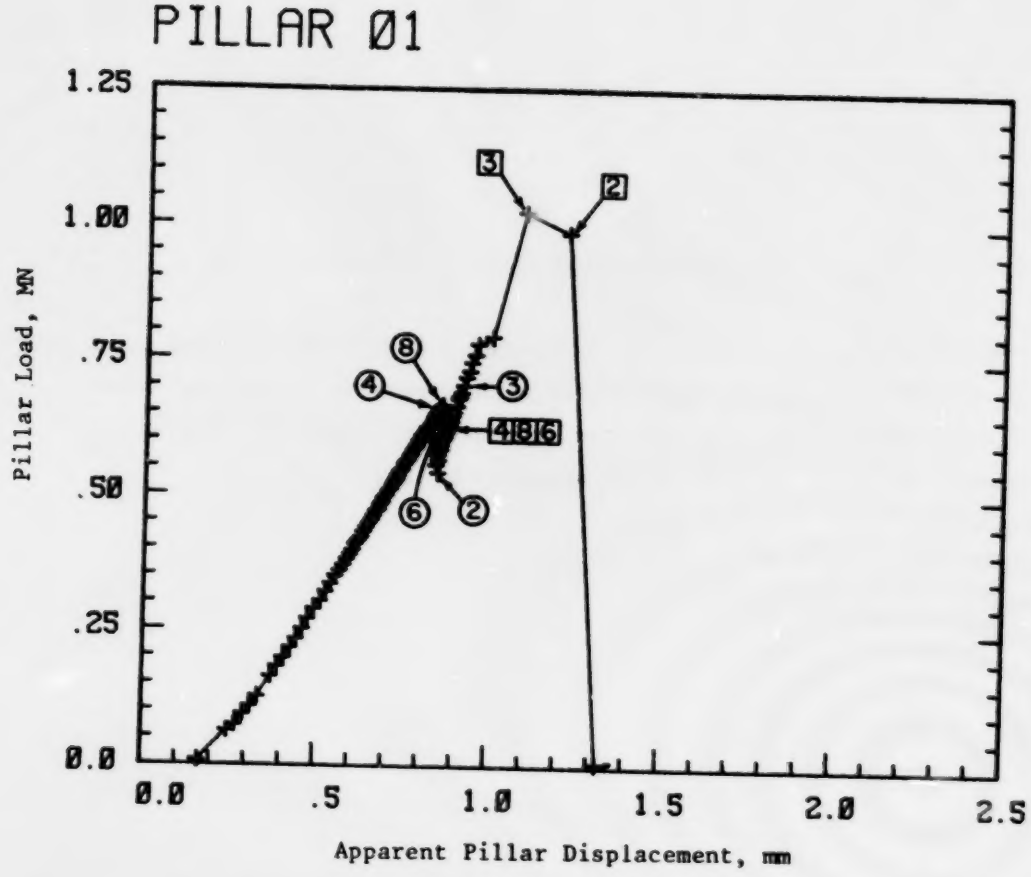

PILLAR Ø1
1.25
1.00
.75
.50
.25
0.0
Pillar Load, MN
0.0
.5
1.0
1.5
2.0
2.5
Apparent Pillar Displacement, mm
3
2
8
4
3
4 8 6
6
2

Fig. B-1

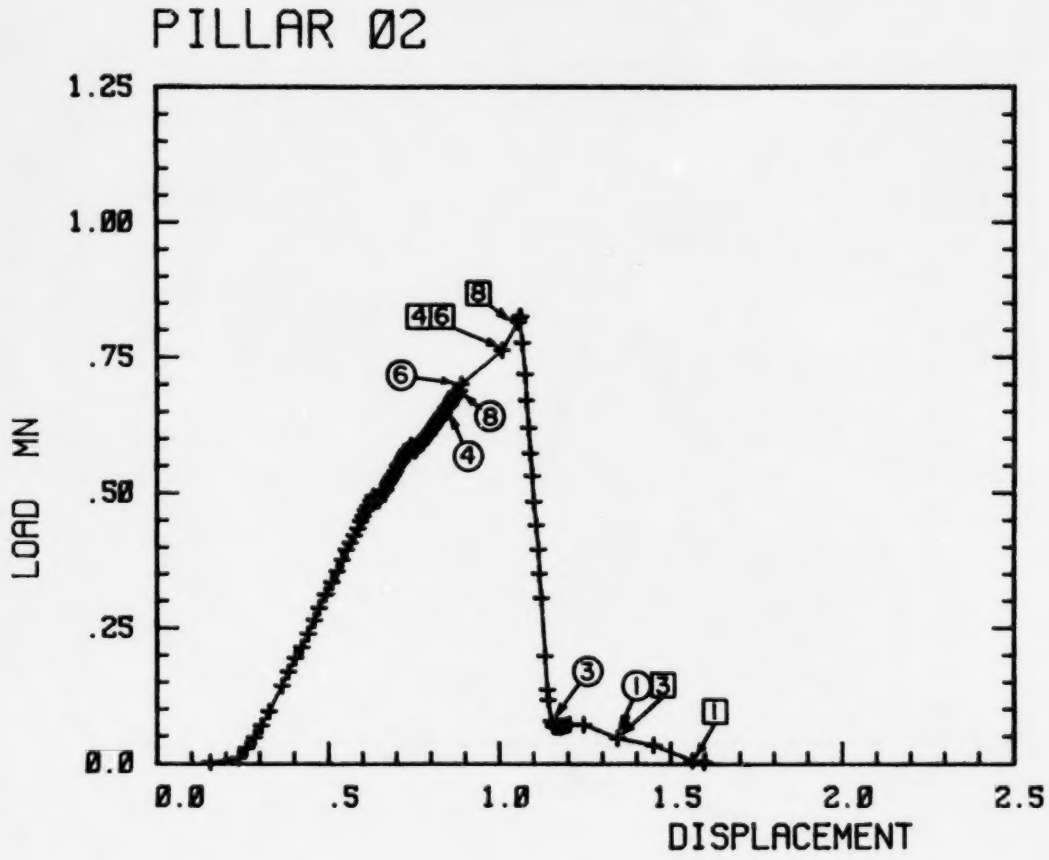

PILLAR 02
1.25
1.00
.75
.50
.25
0.0
LOAD MN
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT
8
4 6
6
8
4
3
1 3
1

Fig. B-2

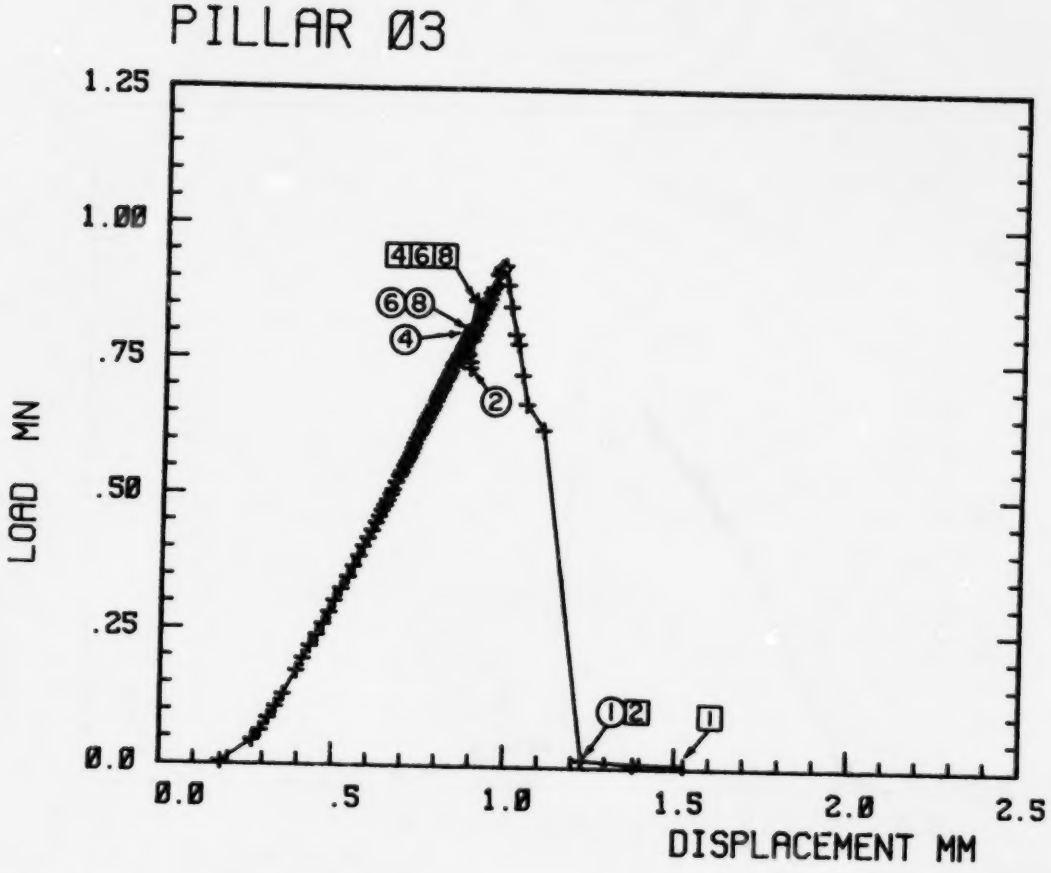

PILLAR Ø3
1.25
1.00
.75
.50
.25
0.0
LOAD MN
4 6 8
6 8
4
2
1 2
1
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT MM

Fig. B-3

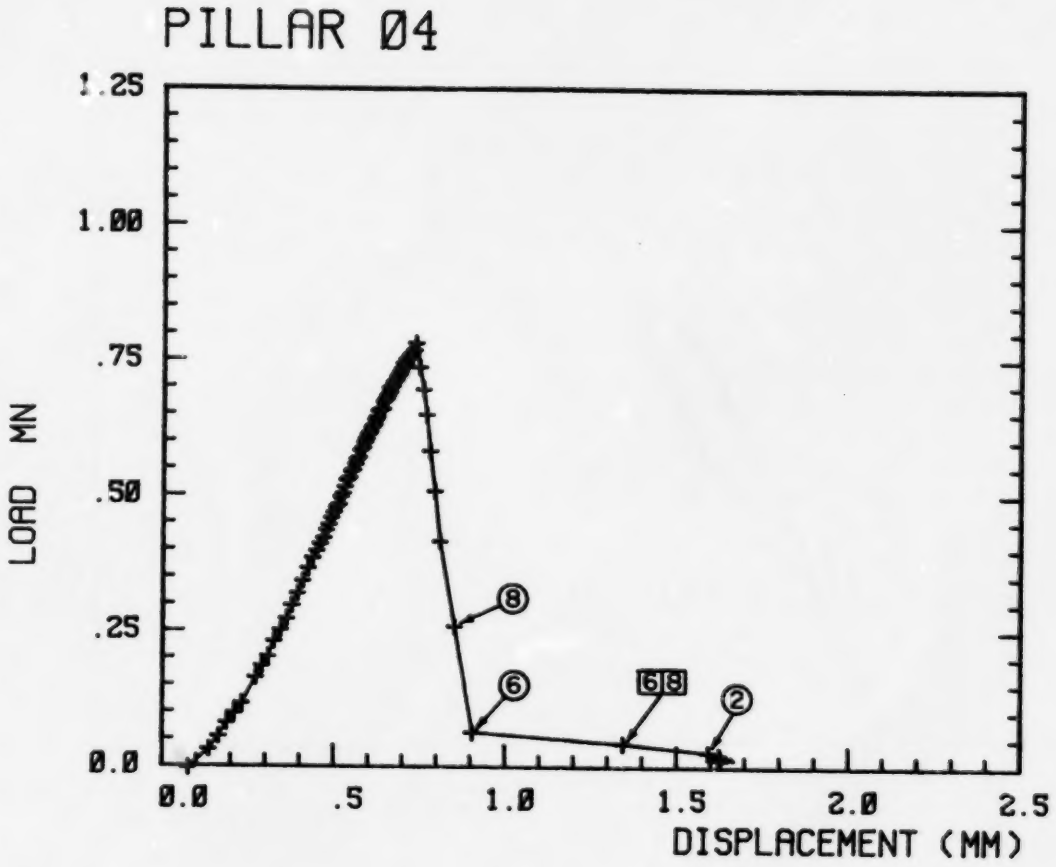

PILLAR Ø4
1.25
1.00
.75
.50
.25
0.0
LOAD MN
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT (MM)
8
6
6 8
2

Fig. B-4

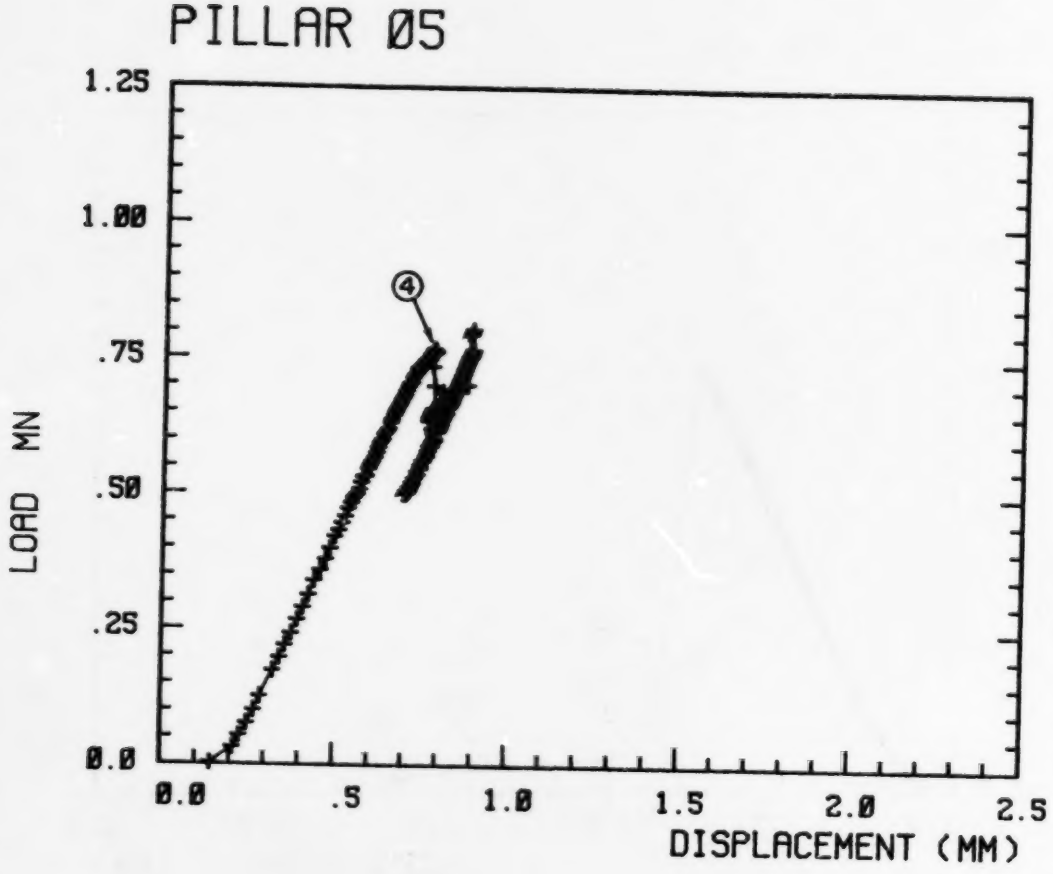

PILLAR Ø5
1.25
1.00
.75
.50
.25
0.0
LOAD MN
④
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT (MM)

Fig. B-5

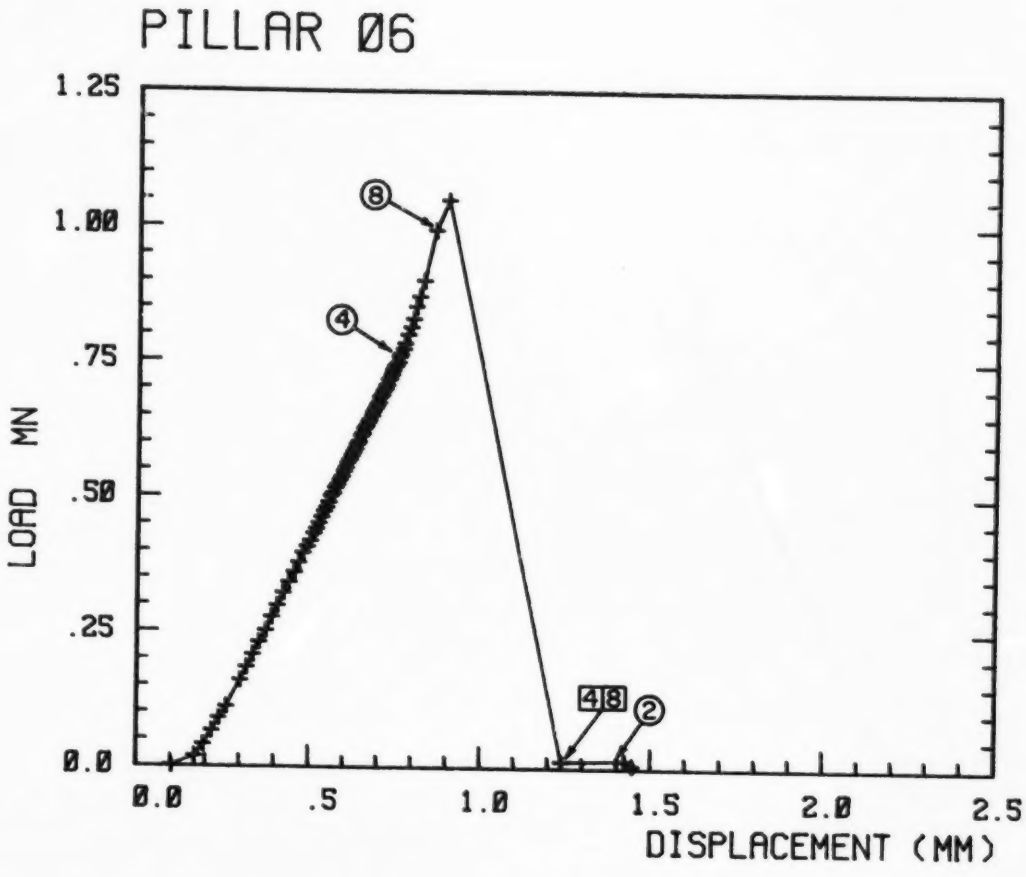

PILLAR Ø6
1.25
1.00
.75
.50
.25
0.0
LOAD MN
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT (MM)
8
4
4 8
2

Fig. B-6

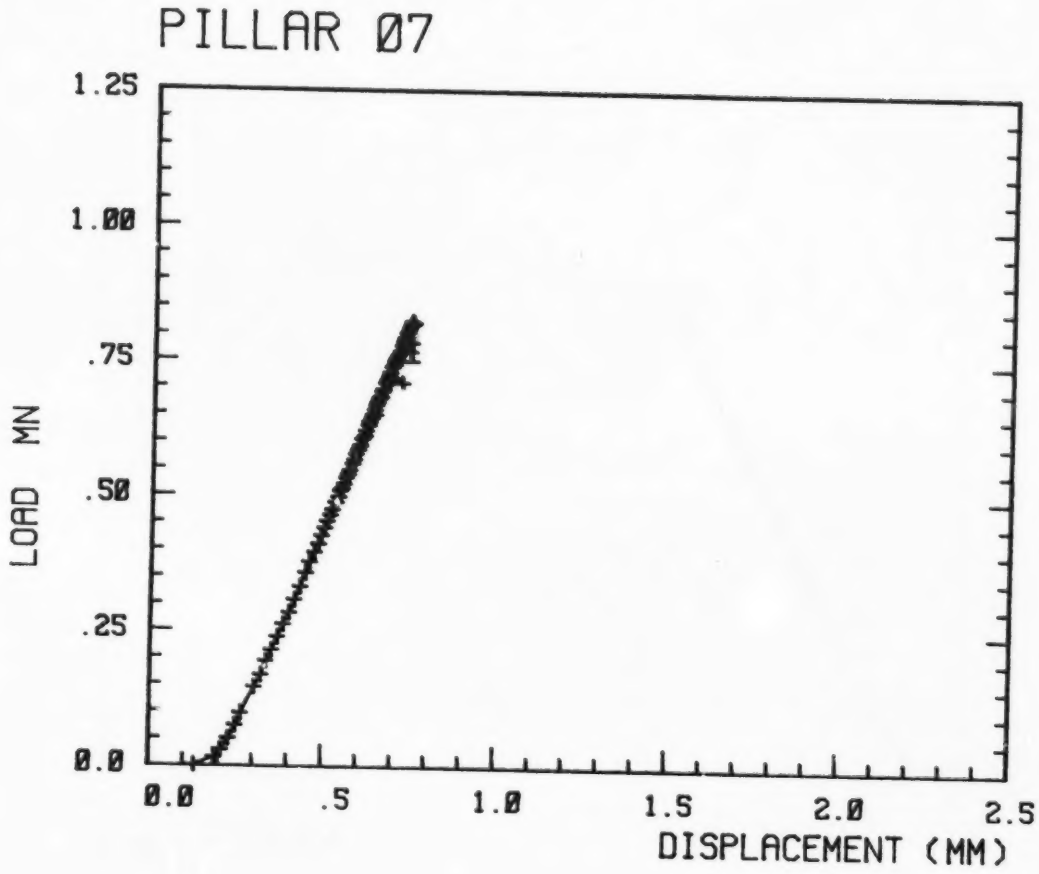

PILLAR 07
1.25
1.00
.75
.50
.25
0.0
LOAD MN
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT (MM)

Fig. B-7

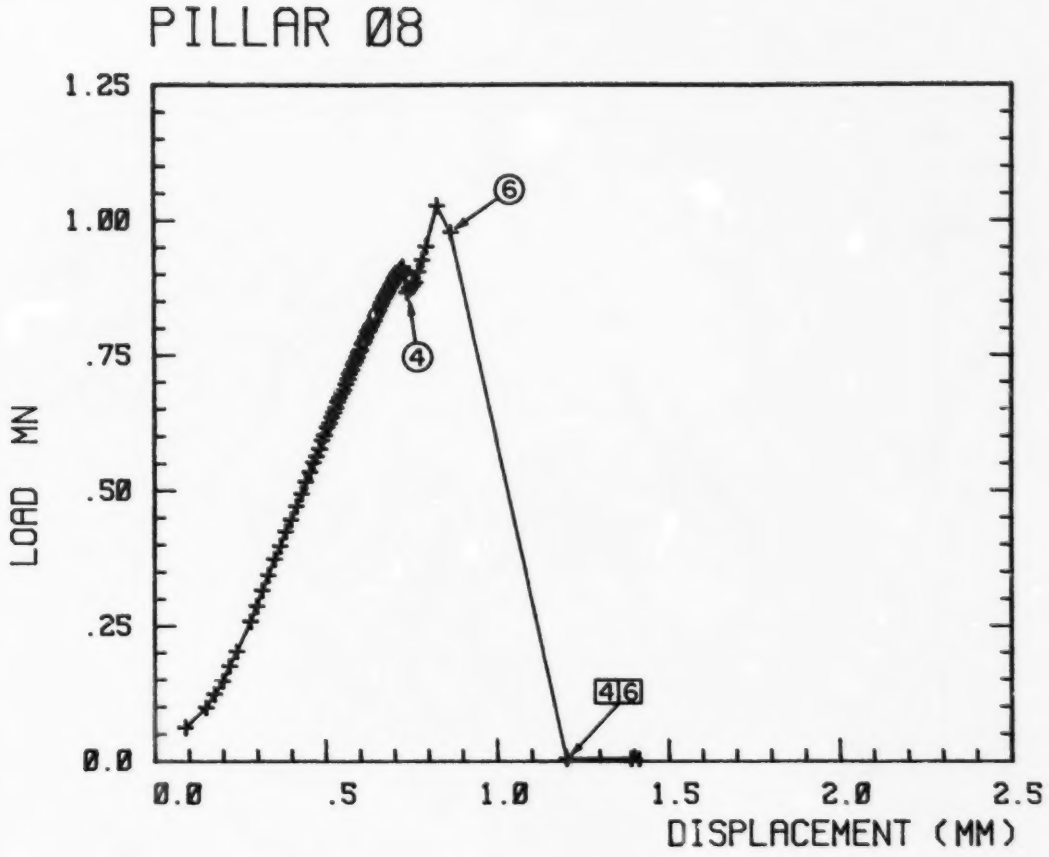

PILLAR Ø8
1.25
1.00
.75
.50
.25
0.0
LOAD MN
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT (MM)
⑥
④
4 6

Fig. B-8

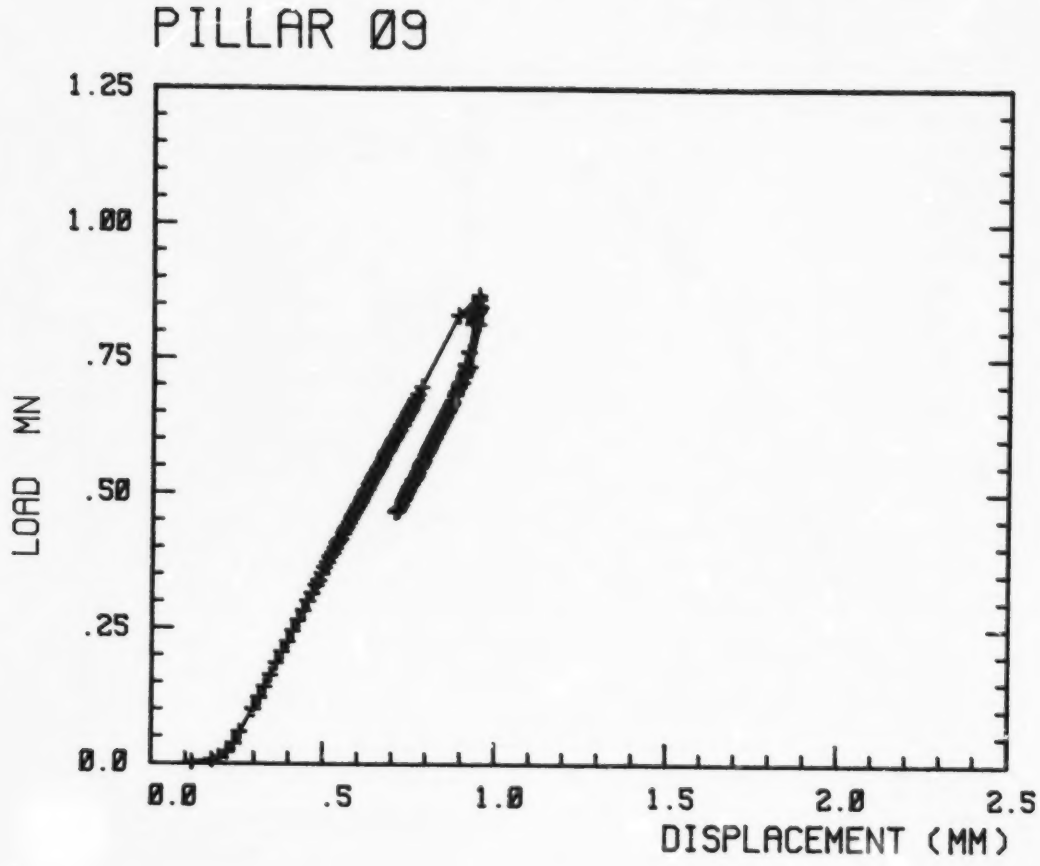
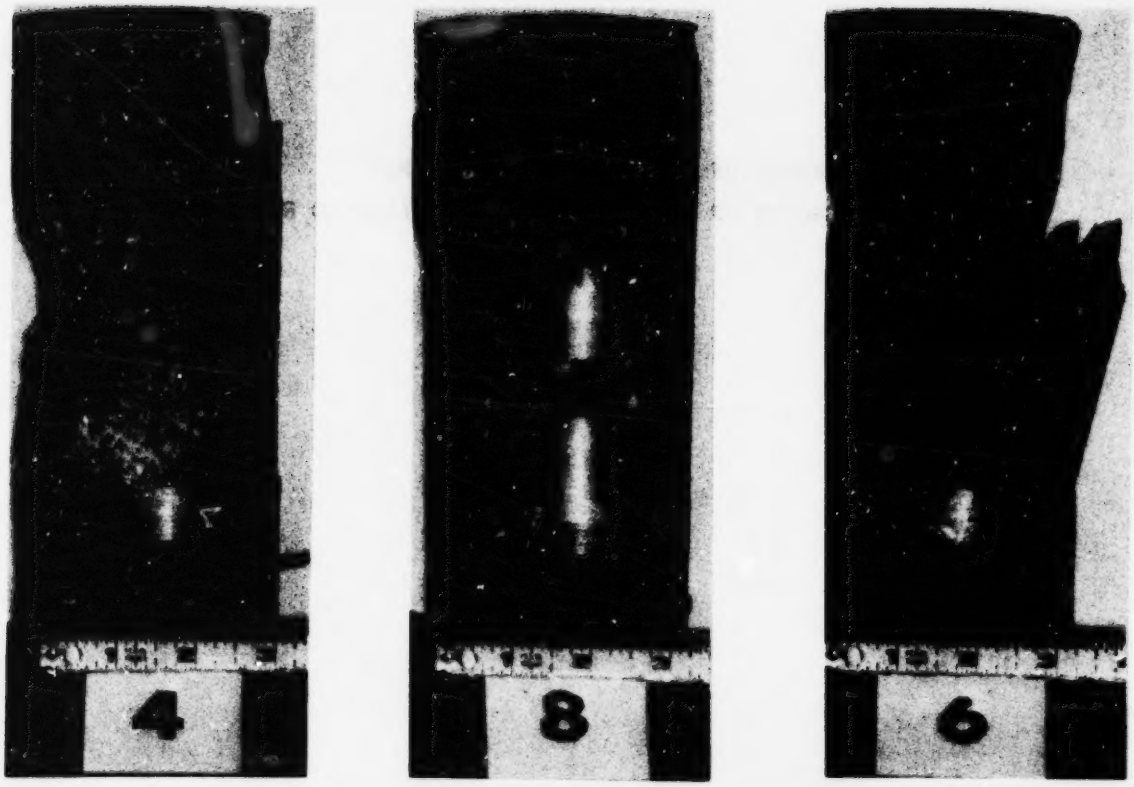
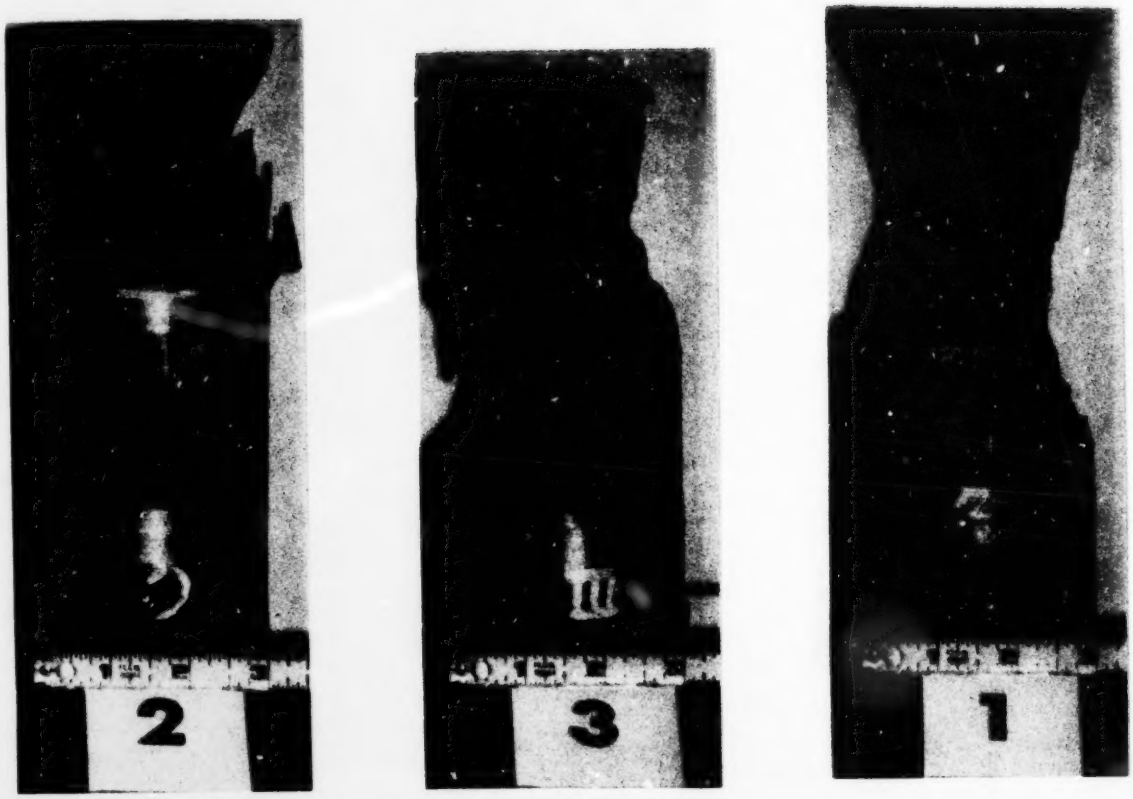

PILLAR Ø9
1.25
1.00
.75
.50
.25
0.0
LOAD MN
0.0
.5
1.0
1.5
2.0
2.5
DISPLACEMENT (MM)

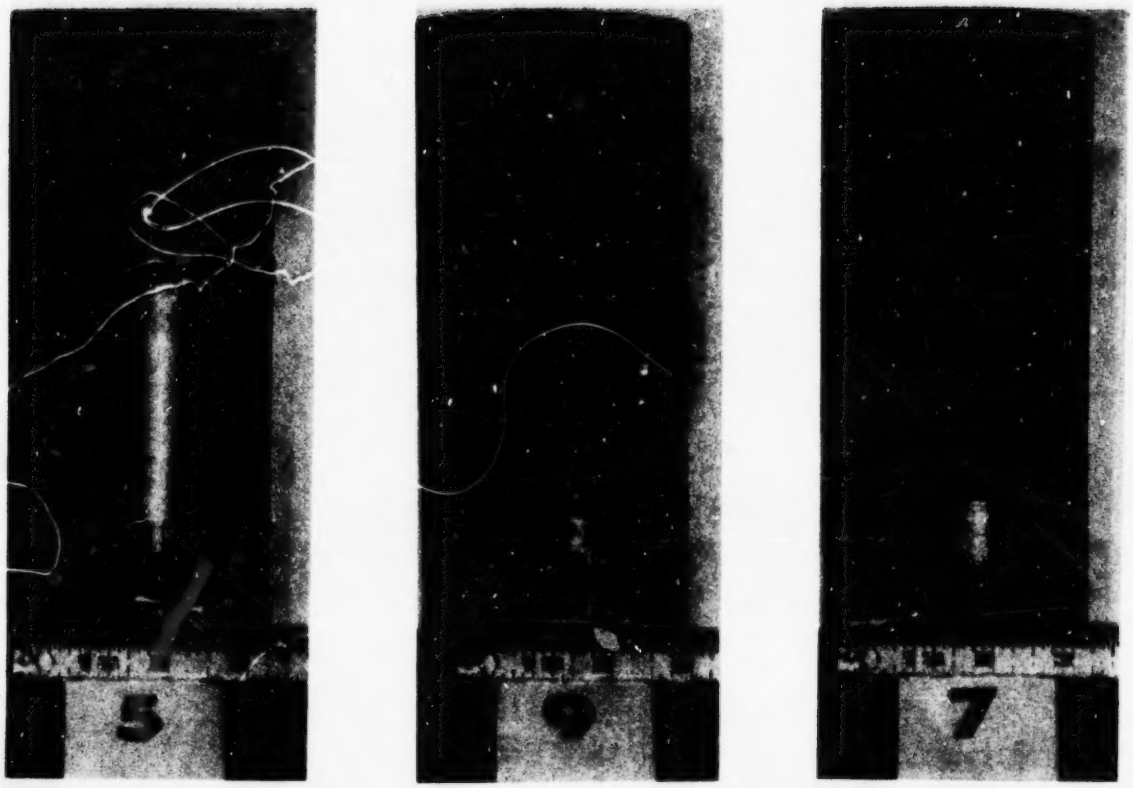
Fig. B-9

APPENDIX C

APPEARANCE OF PILLARS AFTER EXPERIMENT
ARRANGED IN GROUPS OF THREE AND SEQUENCED LEFT TO RIGHT


4
8
6


2
3
1


5
9
7